General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 65, NO. 9 SEPTEMBER 1960

Letters to the Editor

Angular Motion of the Spin Axis of the Tiros I Meteorological Satellite Due to Magnetic and Gravitational Torques

WILLIAM R. BANDEEN

Goddard Space Flight Center
National Aeronautics and Space Administration
Washington, D. C.

AND

WARREN P. MANGER

Astro-Electronic Products Division, Radio Corporation of America
Princeton, New Jersey

The Tiros I meteorological satellite was injected into orbit about the earth on April 1, 1960, at 11h 52m GMT. The purpose of the satellite was to photograph cloud patterns and distribution over the earth [*Stroud,* 1960].

In order to properly command the satellite from the ground to take direct or remote pictures, and in order to analyze these pictures when they are telemetered to the ground, the time, spatial coordinates, and spin-axis attitude of the satellite must be known. Ephemerides based on tracking data from the worldwide Minitrack Station Network and published by the NASA Space Computing Center determine accurately the spatial coordinates as a function of time. It was thought that, except for small perturbations, the spin-axis attitude would be space-stabilized for the nominal 3-month life of the satellite.

The spin rate of Tiros I at injection was 10.0 rpm. The axes of the two television cameras were parallel to the spin axis but pointing in the opposite direction (Fig. 1). A tuned energy-absorption mass device was installed in the satellite to damp out the initial free precession or nutation after separation from the third-stage rocket. It apparently has worked very well. The time of injection and the trajectory of the launch vehicle determined that the coordinates of the satellite spin vector on the celestial sphere should have been the following: declination, +19.8°; right ascension (RA), + 58.6° (Fig. 1).

After several days of picture taking, however, it became apparent from analyses of photographs showing the horizon or identifiable landmarks that the direction of the spin vector (and, hence, the camera axes) was not fixed but was moving southward by as much at 3° to 5° per day (Fig. 2). On April 23, an analysis of photographs indicated that the spin axis had reached its southernmost declination, namely, −30°. At this time its RA had increased to +69.0°. Several days later it was determined from photographs that the spin vector was moving northward again and its RA increasing (eastward) at a greater rate than previously.

The Tiros I orbit is inclined to the equator at 48.4° and is nearly circular, having an apogee of 466 and a perigee of 431 statute miles. Its period is 99.24 minutes. Owing to a torque exerted on the orbit by the earth's bulge, the orbit regresses (westward) around the equator 4.547°/day (Fig. 1). It is apparent from Figure 1 that if the spin vector were to remain fixed in space the westward motion of the orbit would cause an angle to develop between the orbital plane and the spin axis. Since Tiros I has the shape of a short cylinder (19 inches high and 42 inches in diameter), the moment of inertia about its spin axis is larger than the other principal moments of inertia. Hence, when the angle between the orbital plane and the spin axis is greater than zero and less than 90°, a torque due to differential gravity (similar to that exerted by the sun and moon on the earth, causing its precession) will be exerted on the satellite. On investigation this torque was rejected as the primary torque causing the observed forced precession because it would have caused the spin vector to move northward instead of in the observed southerly direction.

The minimum spin vector declination of $-30°$ was reached about April 23. At this time the orbit had regressed 100° and the unit vector **n**, normal to the orbital plane, lay in the same meridional plane as the unit vector **s** along the satellite spin axis. Shortly thereafter when **n** developed a westerly component with respect to **s** and the satellite spin-axis declination was observed moving northward, the possibility that a magnetic couple was the primary force became apparent, and it became the focal point of investigation.

The outcome of this investigation has indicated that the angular motion of the spin axis of Tiros I can be explained quite well by considering two torques: a primary torque caused by the interaction of a magnetic dipole along the satellite spin axis (caused by residual permanent magnetism of ferromagnetic materials or by closed current loops in the instrumentation or by a combination of the two) with the earth's magnetic field, and a secondary torque caused by differential gravity in the earth's gravitational field.

The equation of motion expressing the action of these torques is

$$\frac{d\mathbf{s}}{dt} = \tfrac{1}{2}\epsilon(\mathbf{s}\cdot\mathbf{n})(\mathbf{s} \times \mathbf{n}) + \mu(\mathbf{b} \times \mathbf{s}) \quad (1)$$

where

$$\epsilon = \frac{3\omega_0^2}{\omega_s}\left(\frac{I - J}{I}\right) \qquad \mu = \frac{M}{I\omega_s}\left(\frac{V_0}{R^3}\right)$$

and where

$\mathbf{s}$ = unit vector along the spin axis.

ω_0 = angular velocity of the orbital radius vector.

ω_s = angular velocity of the satellite around its spin axis.

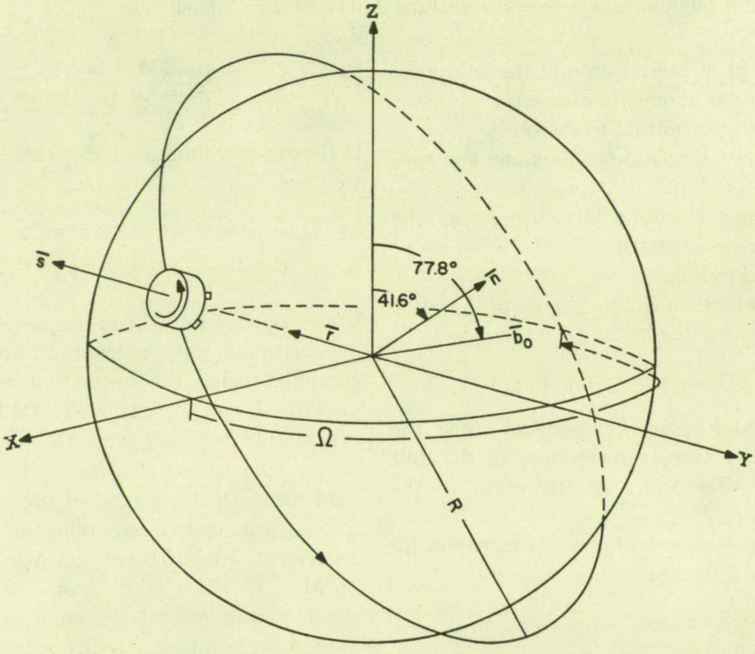

Fig. 1. Tiros I at injection, 1152 GMT, April 1, 1960. X, Y, and Z are space coordinates with origin at the center of the earth and with the X-Y plane in the equatorial plane of the earth. **s** is the unit spin vector of the satellite. The astronomical coordinates of **s** are declination, $+19.8°$; right ascension, $+58.6°$. Ω is the angle from the X axis to the orbital ascending node. The orbital nodes regress at the rate of $-4.547°$ day^{-1} (westward). **n** is the unit vector normal to the orbit. $\mathbf{b}_0$ is the mean normalized magnetic dipole field vector appearing to the satellite in one orbit. **r** is the unit vector from the center of the earth toward the satellite. R is the orbital radius.

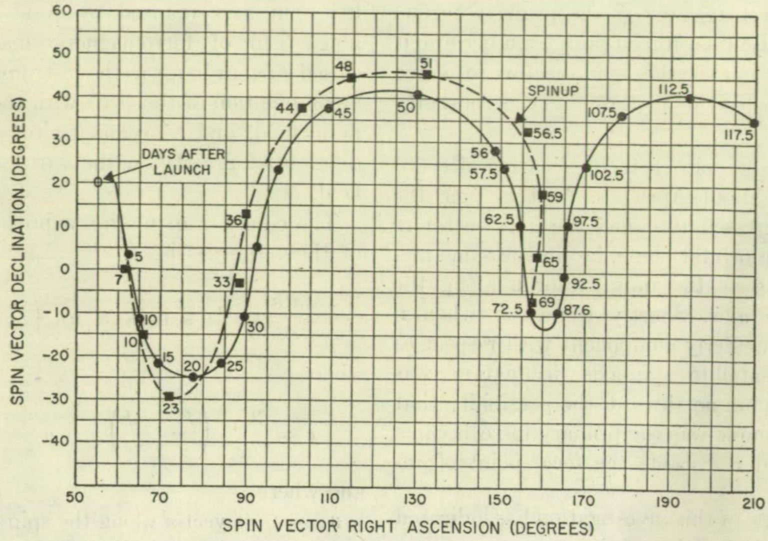

Fig. 2. Observed motion of the Tiros I spin vector based on an analysis of photographs (dashed line) compared with the theoretical motion based on the effects of a magnetic dipole moment along the spin axis and differential gravity (solid line). Declination is +north and −south of the celestial equator. Right ascension is +east of the vernal equinox along the celestial equator. Increased stability of both the theoretical and observed motion is seen after spinup on May 27 (day 56 after launch). The last picture with clearly identifiable landmarks was received on June 9 (day 69 after launch).

I = moment of inertia around the spin axis.
J = transverse moments of inertia.
$\mathbf{n}$ = unit vector normal to the orbit.
M = magnetic dipole moment along the spin axis.
V_0 = magnetic constant for a dipole at the center of the earth.
R = orbital radius.
$\mathbf{b}$ = normalized magnetic dipole field vector for the earth's field

$$\mathbf{b} = \mathbf{i}(-3r_x r_z) + \mathbf{j}(-3r_y r_z) + \mathbf{k}(1 - 3r_z^2)$$

where r_x, r_y, and r_z are components along the space x, y and z axes, respectively, of the unit vector $\mathbf{r}$ from the center of the earth to the satellite.

Representative values of these parameters for Tiros I are the following:

ω_0 = 0.001055 rad sec^{-1}.
ω_s = 1.047 rad sec^{-1}.
I = 170,000 kg cm^2.
J = 124,100 kg cm^2.
M = 896 dyne cm gauss^{-1}
(equivalent of 1 ampere flowing in 1 turn of wire around the satellite base plate).

$$\frac{V_0}{R^3} = 0.19 \quad \text{gauss}$$

If the above values are substituted in equation 1 we have:

$$d\mathbf{s}/dt = \tfrac{1}{2}(8.6 \times 10^{-7})(\mathbf{s}\cdot\mathbf{n})(\mathbf{s} \times \mathbf{n}) + (9.6 \times 10^{-7})(\mathbf{b} \times \mathbf{s}) \qquad (2)$$

where $d\mathbf{s}/dt$ is in radians per second.

Equation 2 was programmed on an electronic computer using the initial injection conditions of Tiros I on April 1, 1152 GMT. The results are plotted together with the observed motion of the spin axis in Figure 2, showing excellent agreement. In this computer run a time function for ω_s was introduced reflecting its observed decrement from 10.0 rpm on April 1 to 9.4 rpm on May 27. (The decay in spin is due to a very small torque caused by eddy currents generated in the spinning satellite by the earth's magnetic field.) On May 27 a pair of spinup rockets was fired at 2133 GMT, increasing ω_s to 12.875 rpm. As is seen from equation 1, greater stability is effected at higher values of ω_s, and this increased stability can be seen in the plot after spinup (Fig. 2).

In this work to date, a theoretical dipole field has been assumed for the earth's magnetic field. For this field the mean magnetic dipole field vector $\mathbf{b}_0$ appearing to a satellite in a Tiros I type of orbit lies in the n–earth axis plane at a colatitude of 77.8° (Fig. 1). Further investigations of the theoretical aspects of this problem are now under way, including the use of a more realistic magnetic field. A detailed paper will be published in the near future.

The Tiros II meteorological satellite, soon to be launched, will carry a radiation experiment as well as two television cameras similar to those in Tiros I. It is especially important for the radiation experiment that the angle between the sun and the satellite spin axis not exceed 35°. It is planned, therefore, to include a variable closed current loop in Tiros II to be commanded from the ground for the purpose of controlling the spin-axis attitude from the ground according to the requirements of the experiment.

Acknowledgment. We should like to express our thanks to I. Ruff and S. Twomey of the U. S. Weather Bureau, and to R. Goerss of RCA, all of whom made contributions to the investigation.

References

Stroud, W. G., Initial results of the Tiros I meteorological satellite, *J. Geophys. Research, 65,* 1643–1644, 1960.

(Received July 13, 1960.)